APPENDIX A

The 28-day Compressive Strength Prediction for Fly Ash Concrete

THEORETICAL BACKGROUND AND COMPUTATIONAL MODEL

The 28-day compressive strength prediction, a basis for predicting compressive strength at the other ages, was developed by reasonably assuming that the 28-day compressive strength varies with unit calcium oxide content in the concrete (C), water to binder ratio (w/b), and ratio of paste volume to void content of the compacted aggregate phase (γ). In this study, the effect of air void is not considered since air void system is hardly necessary in Thailand. It is noted here that the model was created for conventional fly ash concrete, in which aggregates are normally stronger and denser than the paste. For fly ash concrete in normal practice, the compressive strength increases in concrete with higher unit CaO content and lower w/b as illustrated in Fig. A.1.

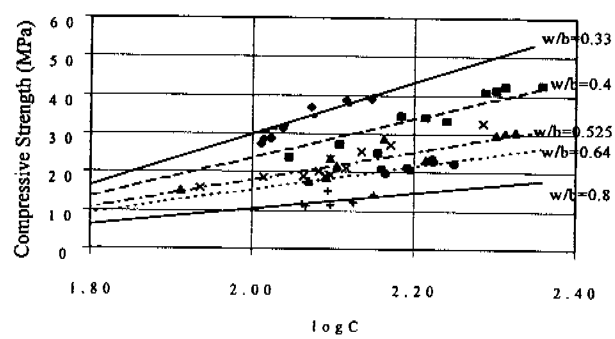

Fig. A.1 Relationship between 28-day compressive strength and logarithm of unit CaO content of fly ash concrete

The compressive strength will decrease when paste content increases much

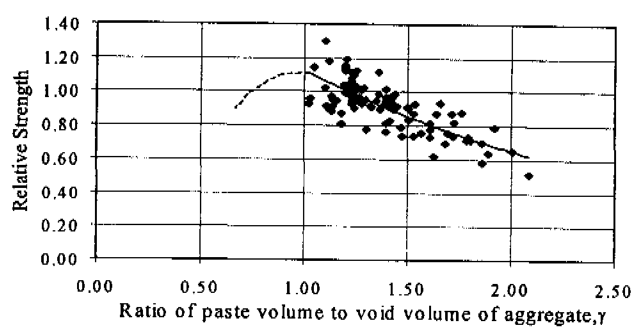

Fig. A.2 Relationship between relative strength and γ-factor

beyond the void of the compacted aggregate (γincreases) as shown in Fig. A.2. To get the optimum compressive strength, the paste not only fills the voids but also creates bonding among aggregate particles. If concrete has too much paste, the mixture will have more water content which results in higher porosity and lower density of the concrete. On the other hand, if concrete has not enough paste, it could not completely fill the void on the aggregate phase and then affecting the bonding among aggregates.

Both cases will cause the lower compressive strength in concrete. Based on the information in Fig. A.1 and Fig. A.2, the equation for predicting 28-day compressive strength of concrete with fly ash was formulated as:

$$f_c(28) = [(16.45\times(w/b)^{-1.26})\times(\log C-1.8)-10.91\times\ln(w/b)+3.96]\times(1.8931\times e^{-0.53\gamma}) \quad (A.1)$$

where $f_c(28)$ is the 28-day compressive strength (MPa), C is the unit calcium oxide content in the combined cement-fly ash powder (kg/m^3 of concrete), w/b is water to binder ratio, γ is the ratio of paste volume to void content of the compacted aggregate phase. Eq. (A.1) can be applied to fly ash concrete that has the applicable range of unit CaO content from 85-230 kg/m^3 of concrete (water content is also limited from 0.3 to 0.8). In some cases, Eq. (A.1) can not be applied to predict the 28-day compressive strength of conventional concrete. Since the cement only concrete has the unit CaO content range from 150-310 kg/m^3 of concrete. This problem leads to the need to construct another model that takes into account the effect of high unit CaO content in one cubic meter concrete. The new model is expressed in Eq. (A.2). To avoid the ambiguity of these two models (A.1 and A.2), the author suggests using Eq. (A.1) for fly ash concrete and Eq. (A.2) for cement only concrete in order to predict the 28-day compressive strength.

$$f'_c(28) = [(-79.095\times(w/c)+63.73)\times\log(CaO)+(93.94\times(w/c)-64.886)] \times(-0.3074\times\gamma+1.355) \quad (A.2)$$

The unit CaO content, C, can be computed from

$$C = [w_{fly\ ash}\times CaO_{fly\ ash} + w_{cement}\times CaO_{cement}] / 100 \quad (A.3)$$

where $w_{fly\ ash}$ and w_{cement} are fly ash and cement content, respectively (kg/m^3 of concrete), $CaO_{fly\ ash}$ and CaO_{cement}, are calcium oxide content in fly ash and cement, respectively (% by weight).

The ratio of paste volume to void content of the compacted aggregate phase is computed from

$$\gamma = \frac{Vp}{Vv} \quad (A.4)$$

where Vp is the volume of paste in a cubic meter of concrete (liter), Vv is the volume of void of compacted aggregate in one cubic meter container (liter), Vc is the volume of cement in one cubic meter of concrete (liter), Vf is the volume of fly ash in one cubic meter of concrete (liter), Vw is the volume of water in one cubic meter of concrete (liter) and Va is the volume of air in one cubic meter of concrete (liter).

However, not only the 28-day compressive strength but also the strength at other ages are necessary in design. To predict the compressive strength at the other ages, the concept of strength development ratio is introduced. Strength development ratio (ϕ) is the ratio of compressive strength of concrete at the time considered, $f_c(t)$, to the compressive strength at one year, $f_c(365)$, by assuming that there might be only negligible increase of compressive strength after 1 year. In this study, the strength development ratio is considered as the function of glass/lime ratio (SiO_2/CaO), water to binder ratio (w/b) and time (t) which can be explained by the concept of pozzolanic reaction and hydration reaction. Finally, the compressive strength of concrete at any time 't' can be predicted by

$$f_c(t) = \frac{\phi(t) \times f_c(28)}{\phi(28)} \quad (A.5)$$

where $f_c(t)$ compressive strength at time t (MPa) and $\phi(t)$, $\phi(28)$ are strength development ratio at time t and 28 days, respectively. The function of strength development ratio can be expressed as

$$\phi(t) = p \times \log(t+1) + q \quad (A.6)$$

where p, which is the slope of the equation, denotes the rate of strength development function and q, which is the y-intercept, denotes the strength development ratio at 0 day. It is realized that the strength development curve should pass through the origin where time is equal to zero since compressive strength of the concrete just after mixing (0 day) shall be zero as shown on Fig. A.3. Therefore, the compressive strength at very early age (earlier than 3 days) can not be accurately predicted using this proposed strength development function.

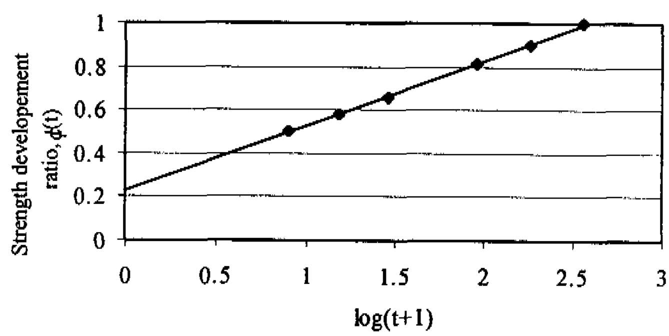

Fig. A.3 Relationship between strength development ratio and logarithm of time, t+1

By the concept of pozzolanic reaction and hydration reaction, it is assumed that the coefficients, p and q have relation with the glass per lime ratio (SiO_2/CaO) for each particular w/b as expressed in the following equation.

$$p = (0.2375 \times w/b + 0.1216) \times (SiO_2/CaO) + (-0.3325 \times w/b + 0.4165) \quad \text{when } \frac{SiO_2}{CaO} \leq 0.86 \quad (A.7a)$$

$$q = (-0.2395 \times w/b - 0.4828) \times (SiO_2/CaO) + (-0.4335 \times w/b + 0.5808) \quad \text{when } \frac{SiO_2}{CaO} \leq 0.86 \quad (A.7b)$$

$$p = (-0.0386) \times (SiO2/CaO) + 0.2415 \times (w/b) + 0.3672 \quad \text{when } \frac{SiO_2}{CaO} \rangle 0.86 \quad (A.8a)$$

$$q = (0.115) \times (SiO2/CaO) - 0.832 \times (w/b) + 0.1685 \quad \text{when } \frac{SiO_2}{CaO} \rangle 0.86 \qquad (A.8b)$$

where
$$SiO_2/CaO = \frac{r \times (SiO_2)_f + (1-r) \times (SiO_2)_c}{r \times (CaO)_f + (1-r) \times (CaO)_c} \qquad (A.9)$$

where SiO_2 is total SiO_2 content in both cement and fly ash (kg/m^3 of concrete), CaO is total CaO content in both cement and fly ash (kg/m^3 of concrete), r is replacement ratio of fly ash in total powder content by weight, $(SiO_2)_f$, $(SiO_2)_c$ are SiO_2 content in fly ash and cement, respectively (%) and $(CaO)_f$, $(CaO)_c$ are CaO content in fly ash and cement, respectively (%).

As shown in Fig. A.4, the rate of strength development, p, increases with increase of glass to lime ratio due to the increase of pozzolanic reaction when glass content increases under the condition of sufficient $Ca(OH)_2$ paste environment. It can be noted by observing Fig. A.4 and Fig. A.5 that the rate of strength development increases up to the glass to lime ratio about 0.86 whereas beyond 0.86, the glass content will be too much so that the concentration of $Ca(OH)_2$ in the pore solution is not enough for processing the pozzolanic reaction. So the rate of strength development gradually decrease. The rate of strength development also increases with w/b because paste with higher w/b has more water for the reactions.

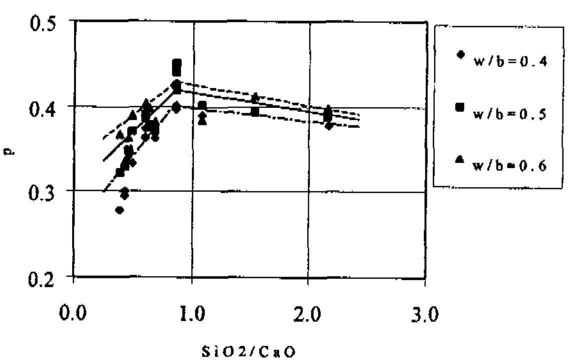

Fig. A.4 Relationship between p and SiO_2/CaO

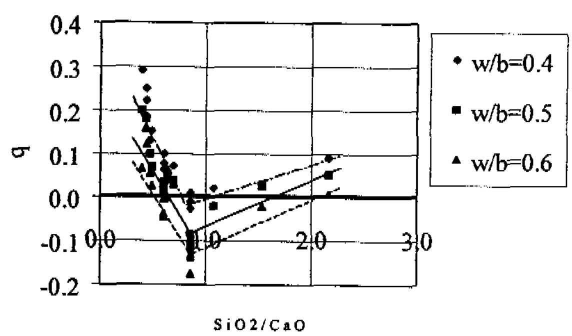

Fig. A.5 Relationship between q and SiO_2/CaO

VERIFICATION OF COMPRESSIVE STRENGTH PREDICTION MODEL

The verification of the 28-day compressive strength model was presented in the form of comparison between experimental data from various sources and computed results from the model as shown in Fig. A.6.

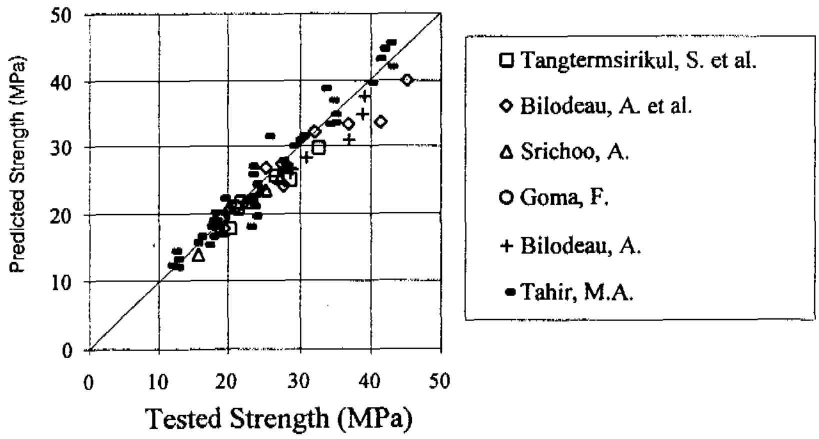

Fig. A.6 Comparison between the tested and predicted 28-day compressive strength

The verification of 3-day, 90-day, 180-day and 365-day strength by using the 28-day compressive strength model together with the strength development ratio were presented in Fig. A.7a-A.7d (Tahir, M.A.).

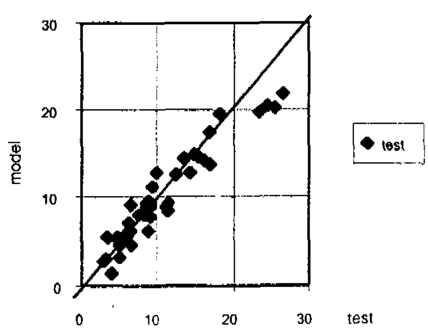

Fig. A.7a The 3-day compressive strength

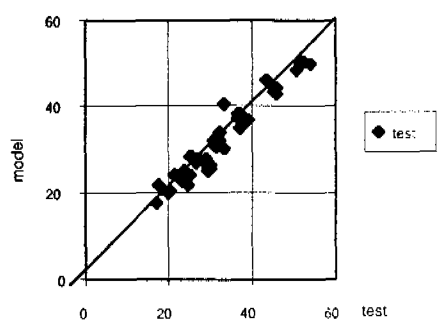

Fig. A.7b The 90-day compressive strength

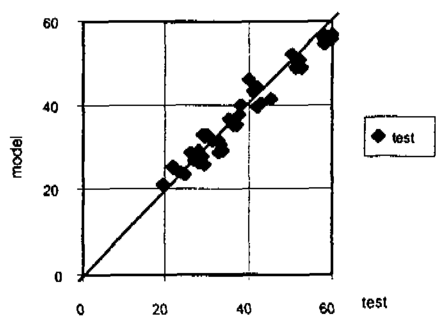

Fig. A.7c The 180-day compressive strength

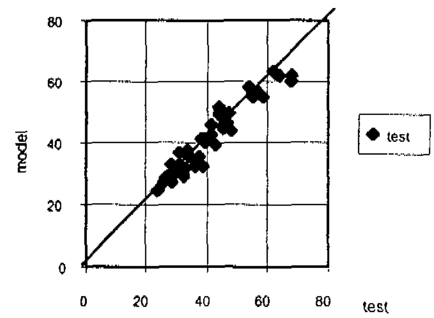

Fig. A.7d The 365-day compressive strength